Dynamics and hadronization at intermediate transverse momentum at RHIC

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Abstract. The ultra-relativistic heavy-ion program at RHIC has shown that at intermediate transverse momenta ($p_T \simeq$ 2-6 GeV) standard (independent) parton fragmentation can neither describe the observed baryon-to-meson ratios nor the empirical scaling of the hadronic elliptic flow (v_2) according to the number of valence quarks. Both aspects find instead a natural explanation in a coalescence plus fragmentation approach to hadronization. After a brief review of the main results for light quarks, we focus on heavy quarks showing that a combined fragmentation and quark-coalescence framework is relevant also here. Moreover, within relativistic Langevin simulations we find evidence for the importance of heavy-light resonances in the Quark-Gluon Plasma (QGP) to explain the strong energy loss and collective flow of heavy-quark spectra as inferred from non-photonic electron observables. Such heavy-light resonances can pave the way to a unified understanding of the microscopic structure of the QGP and its subsequent hadronization by coalescence.

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INTRODUCTION

Experimental data from the Relativistic Heavy Ion Collider (RHIC) during the past few years have shown convincing evidence for a state of matter with energy densities, ε, in substantial excess of the expected critical one, i.e., $\varepsilon \simeq$ 15-20ε_c with $\varepsilon_c \simeq 1$ GeV/fm^{-3}. In the standard picture before 2003 the main concern in the study of produced hadrons at high transverse momentum (p_T) was the underlying modification of partonic spectra due to interactions in such a hot and dense medium, that would reflect in a similar pattern for all hadrons through independent fragmentation. Indeed, one of the most exciting observations at RHIC has been the suppression of high-p_T particles in agreement with the non-abelian radiative energy-loss theory within perturbative QCD (pQCD) [1]. However, for light hadrons the observations of an anomalous baryon-to-meson production ratio at intermediate p_T up to $\simeq$ 6 GeV and a scaling of the elliptic flow with the number of quark constituents, has enforced revisions of an independent fragmentation model for hadronization. Instead coalescence processes among massive quarks appear to be a convenient picture that can naturally and quantitatively account for the main features of light hadron production at intermediate p_T [2, 3, 4, 5].

For heavy quarks (charm (c) and bottom (b)), the energy loss predicted by pQCD [6] turned out to be insufficient (at variance with the light quark case) to account for the observed large nuclear suppression (small R_{AA}) and collectivity (large v_2) in non-photonic single-electron spectra [7, 8, 9, 10, 11]. Here the challenge is mainly in the

understanding of the in-medium quark interactions, even if the acquired knowledge on the hadronization mechanism from light quarks plays a significant role as well.

Lattice QCD (lQCD) results suggest that resonance structures survive in meson-correlation functions at moderate temperatures [12] above T_c. Two of us have therefore suggested an effective model for heavy-light quark scattering via D and B resonances [13]. To study the consequences of such interactions for the modification of the heavy-quark (HQ) distributions, a Langevin simulation has been performed to trace the evolution of HQ distributions through the fireball in heavy-ion Collisions (HICs) [14, 15]; hadronization has been modeled by a coalescence model similar to the one applied to light quarks [2, 3]. It has been found that the effect of resonant heavy-light scattering is crucial [15] and also provides a reasonable agreement with semileptonic $e^{\pm}$ spectra at RHIC data [8, 11, 10].

We note that for heavy quarks (heavy-light) quark-antiquark resonances provide the dominant medium effects on their distributions close to T_c, which then naturally merges into a coalescence-type description for hadronization processes [16].

MODIFICATION OF HADRONIZATION MECHANISM

Hadronization at asymptotically large momentum can be described by a set of fragmentation functions $D_{a/H}(p/P)$ that parametrize, in a universal way, the probability that a hadron H with momentum P is created from a parton a with momentum p in the vacuum. Fragmentation functions have been measured in e^+e^- collisions and work well for hadron production at p_T> 2 GeV also in pp collisions at RHIC energies. Therefore it was expected that in this p_T regime the QGP could be probed by focusing on modifications of the spectra, $E\mathrm{d}N/\mathrm{d}^3p$, at the parton level; but from Au+Au collisions it became clear that this is not the case at least up to $p_T \simeq 6$ GeV. Two puzzling observations lead to this conclusion: (a) baryons are much more abundant than predicted by fragmentation. A ratio $\bar{p}/\pi \approx 1$ between 2 and 4 GeV/c has been measured, see Fig. 1, much larger than the value of ≈ 0.2 predicted by leading-twist pQCD. A similar trend is observed for p/π, Λ/K_s^0, i.e., p, $\bar{p}$ and Λ's do not seem to suffer jet quenching. The pertinent nuclear modification factors, R_{AA}, are close to 1, unlike those of light mesons for which $R_{AA} \approx 0.2$ in central collisions; (b) the elliptic flow of all identified hadrons is found to scale according to a quark-number scaling as reflected in a universal behavior of $v_{2,H}(p_T/n)/n$ where n is the number of constituent quarks in hadron H. In particular, recent data for the $\phi(1020)$ also follow the scaling, suggesting the dominance of the quark content rather than the mass effect, in agreement with the coalescence prescription [17].

The main reason for the inadequacy of a pure fragmentation picture is the high density of the matter created in HICs. In such an environment one may expect that quarks could just coalesce into hadrons: three quarks into a baryon, a quark-antiquark pair into a meson. In such a picture baryons with momentum p_T are mainly produced from quarks with momenta $\simeq p_T/3$, while mesons with the same momentum mainly arise from quarks with momenta $\simeq p_T/2$. This is contrary to the fragmentation process where baryon production is suppressed with respect to mesons as more quarks are needed from the vacuum. A coalescence model that is based on the simple overlap of the quark-distribution function with a hadron-wave function has been developed to implement the

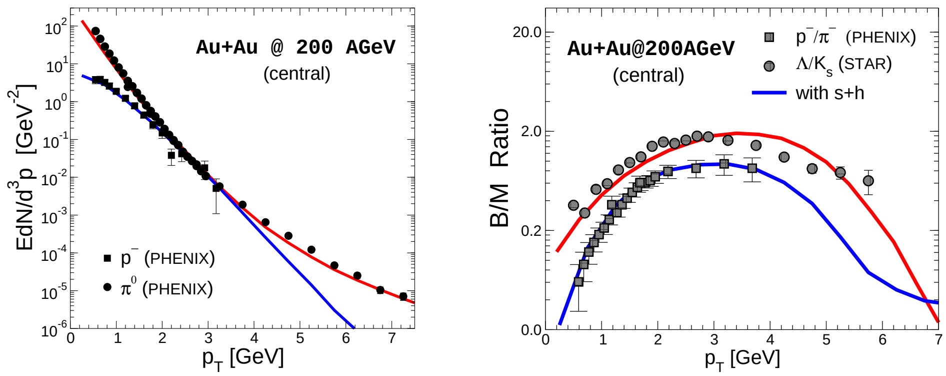

FIGURE 1. Left: π and p^- transverse-momentum spectra in $\sqrt{s}$=200 AGeV Au+Au collisions. RHIC data [18, 19] are shown by circles (π^0) and squares ($\overline{p}$), lines are results from coalescence. Right: experiment vs. coalescence results for baryon-to-meson ratios for p/π (lower part) and Λ/K_s^0 (upper part).

physical ideas sketched above [2]. In such a model the transverse-momentum spectrum of hadrons that consists of n (anti-) quarks is given by the overlap between the hadron-wave function and n quark phase-space distribution functions, $f_q(x_i, p_i)$:

$$\frac{\mathrm{d}N_H}{\mathrm{d}^2P_T} = g_H \int \prod_{i=1}^{n} \frac{\mathrm{d}^3\mathbf{p}_i}{(2\pi)^3 E_i} p_i \cdot \mathrm{d}\sigma_i \, f_q(x_i, p_i)\, f_H(x_1..x_n; p_1..p_n)\, \delta^{(2)}\left(P_T - \sum_{i=1}^{n} p_{T,i}\right) \;; \quad (1)$$

$\mathrm{d}\sigma$ denotes an element of a space-like hadronization hypersurface, f_H is the Wigner distribution function of the hadron and g_H the probability of forming a color-neutral object with the spin of the hadron from n colored quarks. Therefore it is assumed that the probability of coalescence is simply given by the phase-space distance weighted by the wave function of the produced particle Eq. (1). In such an approach constituent-quark masses are included representative for non-perturbative effects. This is a further assumption that can be relaxed for heavy quarks owing to the smaller effect of the QCD vacuum on their masses. The distributions $f_q(x_i, q_i)$ are fixed as homogeneous Boltzmann distributions with an average radial flow $\langle \beta \rangle$ =0.35 for $p_T < 2$ GeV, and quenched minijets for $p_T > 2$ GeV. The volume is fixed to reproduce the measured transverse energy at given centrality. In the left panel of Fig. 1, the p and π spectra obtained from the quark-coalescence model are shown together with the experimental data from PHENIX [18, 19].

The resulting p/π ratio is shown in the right panel of Fig. 1 by lower lines [20], a similar effect is seen also for the Λ/K_s^0 ratio (upper lines) [21]. Similar conclusions are reached in other studies based on quark coalescence [4, 5].

HEAVY-QUARKS AT HIGH TEMPERATURES

Heavy quarks (b, c) are produced out of thermal equilibrium in the very early stage of the reaction; due to their large mass a perturbative evaluation of their in-medium interactions was expected to be reliable also at relatively small p_T. However, a small nuclear modification factor, $R_{AA} \simeq 0.3$, has been deduced from semileptonic electron

spectra associated with decays of D- and B-mesons [8, 11], comparable to the pion one. Such a value is incompatible with pQCD jet-quenching mechanisms [6]. This statement is strengthened by the observed v_2 of up to 10% [7, 10], indicating substantial collective behavior of charm (c) quarks [3]. Moreover, a consistent description of R_{AA} and v_2 cannot be achieved even if one artificially upscales the transport coefficients within pQCD energy-loss calculations [14]. This suggests that the physics underlying the heavy quark observables is not only a matter of a global evaluation of the interaction strength, but there is an opportunity for a more detailed understanding of the microscopic nature of the interaction (most likely of non-perturbative origin) and of the hadronization mechanism, as we briefly review in the following.

A hint on non-perturbative interactions of heavy quarks in the medium is provided by lQCD computations which exhibit resonance structures in meson correlation functions at moderate temperatures [12, 22]. Along this line two of us have suggested that D- and B-resonance exchange in the $\bar{q}-Q$ channel may be the dominant scattering process that drives the HQ dynamics [13]. To evaluate the consequences of such a picture we have built a model based on an effective Lagrangian:

$$\mathscr{L} = Q\,\frac{1+\not{v}}{2}\,\Phi\,\Gamma\,\bar{q} + \text{h.c.} \tag{2}$$

where Φ=D, B. We have calculated elastic $Q+\bar{q}\rightarrow Q+\bar{q}$ scattering amplitudes via Φ exchange in the s- and u-channel. The existence of one Φ state (e.g., a pseudoscalar J^P=0^-), is assumed together with a minimal degeneracy following from chiral and HQ symmetries, represented by Dirac matrices Γ=1, γ_5, γ^μ, $\gamma_5\gamma^\mu$ in Eq. (2).

The application to HICs is realized by treating HQ kinetics in the QGP as a relativistic Langevin process [15]:

$$\frac{\partial f}{\partial t} = \frac{\partial(\gamma p f)}{\partial p} + \frac{\partial^2(D_p f)}{\partial p^2}\ ; \tag{3}$$

γ and D_p are drag and (momentum) diffusion coefficients which determine the approach to equilibrium and satisfy the Einstein relation, $T = D_p/\gamma M_Q$. The bulk medium is modeled by a spatially homogeneous elliptic thermal fireball which expands isentropically. Finally, hadronization is treated via coalescence at T_c=180 MeV, see Eq. (1), plus fragmentation processes evaluated as $f_{c,b}(p_T)*[1-P_{c,b\rightarrow(D,\Lambda_c),(B,\Lambda_b)}(p_T)]$, where $P_{c,b\rightarrow(D,\Lambda_c),(B,\Lambda_b)}$ is the probability for a heavy quark to coalesce.

For 200 AGeV Au+Au collisions results from the Langevin simulation including hadronization by coalescence+fragmentation (left) and fragmentation only (right) are shown in Fig. 2 together with experimental data [8, 9]. It is obvious that elastic scattering in a pQCD scheme is insufficient to account for the small R_{AA}, independent of the hadronization scheme applied. The red band shows the full calculation with c,b quarks that scatter in the presence of hadron-like resonances with a width $\Gamma \simeq$ 0.4-0.75 GeV (representing the interaction strength), supplemented by the pQCD elastic scattering in color non-singlet channels (dominated by gluons). We note that the contamination of single electrons from B decays is significant already at $p_T \sim 2$ GeV (corresponding to a crossing of c and b spectra at around $p_T\sim$4-5 GeV). Thus the inclusion of B mesons (despite the inherent uncertainties in the b/c ratio) is mandatory to draw reliable conclusions on the interaction processes underlying the experimental results.

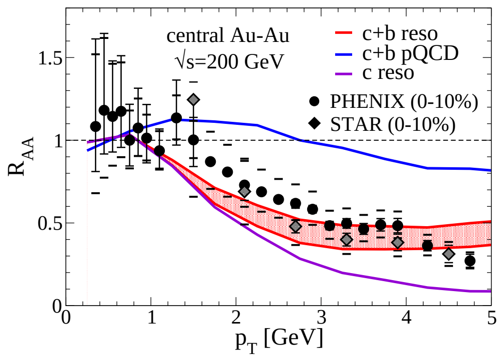

FIGURE 2. Nuclear modification factor for single electrons, including coalescence and fragmentation at hadronization (left panel) and only with fragmentation (right panel), compared to RHIC data [10, 11].

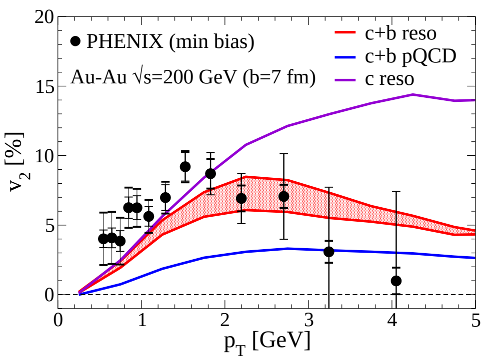

FIGURE 3. Elliptic flow for single electrons, including coalescence and fragmentation at hadronization (left panel) and only with fragmentation (right panel), compared to RHIC data [10].

When comparing the band in the left and right panel of Fig. 2 we can see a clear coalescence effect of hadronization in terms of an increase in the R_{AA} at $p_T \sim$ 1-4 GeV. This effect becomes more significant via a simultaneous enhancement of the elliptic flow v_2 [3, 15], see Fig. 3 This behavior is typical of a coalescence mechanism, reversing the usual correlation between R_{AA} and v_2, and allows for a reasonable description of the experimental data on both R_{AA} and v_2. Very recently, a Brueckner many-body scheme for in-medium T-matrices for HQ scattering off light quarks [23] has been evaluated starting from lQCD potentials. The existence of D and B-like resonances has been confirmed; furthermore, when embedding the pertinent drag and diffusion coefficients in the model described above, a comparable (or even better) agreement with the data is found [23].

CONCLUSIONS

The first stage of RHIC program has shown clear signs of modifications of the hadronization mechanism in the light-quark sector relative to pp collisions. There are several evidences that hadronization proceeds through the coalescence of (massive) anti-/quarks which are close in phase space. The modification of hadronization for light quarks also

seems to play a role in the new challenge posed by heavy-quark probes. Here, the main issue is the dominant interaction mechanism (HQ diffusion) and its relation to the microscopic structure of the QGP. We have presented a scenario based on the existence of B- and D-like resonances in the QGP up to $T = 2\,T_c$. Reasonable agreement with experimental data is achieved owing to a positive interplay between the resonance scattering mechanism and the hadronization by coalescence. We note that such an approach provides an inherent consistency between the in-medium interactions of HQs and the subsequent hadronization by coalescence: a pole in the quark-antiquark propagator above T_c can be viewed as a precursor of recombination.

Finally, it is important to keep in mind the interrelations of open and hidden charm, if regeneration makes up a good fraction of the charmonium yield as expected at RHIC and LHC. In this case, the study of B and D distributions can be related to that of J/ψ and Υ due to the underlying common c, b distributions; the consistency of such a picture should be checked in the near future.

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